Supporting Information

The Formation of Core Cross-Linked Star Polymers Containing Cores Cross-Linked by Dynamic Covalent Imine Bonds

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Experimental Section:

All chemicals were purchased from Sigma-Aldrich or Alfa Aesar and were used as received without further purification.

$^1$H and $^{13}$C NMR spectra were recorded on a Bruker Avance 300 spectrometer at 300 and 75 MHz, respectively, with the residual solvent signal as an internal standard. FTIR spectroscopy was performed on a Varian 800 FTIR instrument (Varian Inc.). High-resolution mass spectrometry was performed on a Waters LCT premier mass spectrometer (Waters Inc.). Gel permeation chromatography (GPC) was conducted on a Varian ProStar instrument (Varian Inc.) equipped with a Varian 325 UV-vis dual wavelength detector (254 nm), a Viscotek 3580 differential RI detector, and a pair of PL gel 5 µm Mixed D 300 × 7.5 mm columns with guard column (Polymer Laboratories Inc.) in series. Near monodisperse polystyrene standards (Polymer Laboratories) were used for calibration. Data collection was performed with Galaxie software (Varian Inc.) and chromatograms analyzed with the Cirrus software (Varian Inc.) and Astra software (Wyatt Technology Corp.).

MALDI-TOF analysis was performed on a Bruker Microflex (Bruker Daltonics). Samples for analysis were prepared by mixing solutions of dithranol (20 mg/mL) and AgTFA (10 mg/mL) with solutions of the polymer sample (10 mg/mL) in amounts of 100 µL: 40µL: 20µL respectively. 0.6 µL of solution was spotted onto the MALDI plate for analysis. Calibration was carried out against near monodisperse polystyrene standards. Data collection was performed with Flexcontrol and analysis of spectra was performed using Flexanalysis software.

4-Vinylbenzaldehyde$^{[1]}$:

A solution of 4-vinylbenzyl chloride (20.01 g, 130.2 mmol) and sodium acetate (12.9 g, 157.1 mmol) in (CH$_3$)$_2$SO (60 mL) was heated at 45 °C whilst stirring under N$_2$ for 24 h. The reaction mixture was transferred to a separating funnel and H$_2$O (100 mL) added. The product was extracted into EtOAc (3 × 100 mL). The organic extracts were combined and dried over MgSO$_4$, filtered and evaporated to dryness to afford crude 4-vinylbenzylacetate as a pale yellow oil (24.81 g, 99%), which was dried under high vacuum. 20 % NaOH$_{aq}$ (50mL) was added to a stirred solution of crude 4-vinylbenzylacetate (24.81 g, 140.8 mmol) in EtOH (50 mL). The reaction mixture was heated at reflux for 4 h then transferred into a separating funnel with EtOAc (100 mL). The aqueous layer was washed with EtOAc (2 × 100 mL), and the organic extracts were combined and dried over MgSO$_4$, filtered and evaporated to dryness to afford crude 4-vinylbenzalcohol as a brown oil (26.36 g, 100%) which was dried under high vacuum. A solution of (COCl)$_2$ (8.55 g, 67.4 mmol) in CH$_2$Cl$_2$ (50 mL) was cooled to -78 °C whilst stirring under N$_2$. A solution of (CH$_3$)$_2$SO (10.67 g, 134.8 mmol) in CH$_2$Cl$_2$ (50 mL) was added dropwise over 15 min, and then a solution of crude 4-vinylbenzylalcohol (8.22 g, 61.3 mmol) in CH$_2$Cl$_2$ (50 mL) was added dropwise over 30 min. NEt$_3$ (19.84 g, 196.0 mmol) was added to the reaction mixture and the solution was allowed to reach room temperature. The reaction mixture was left to stir under N$_2$ for 16 h, then transferred into a separating funnel with HCl$_{aq}$ (1 M, 100 mL) and H$_2$O (100 mL). The organic layer was collected and dried over MgSO$_4$, filtered and evaporated to dryness to afford crude brown oil (8.09 g, 100 %). The crude product was purified by vacuum distillation to afford 4-vinylbenzaldehyde as a clear oil (4.2 g, 52%). $^1$H NMR (CDCl$_3$): δ 5.44 (d, 1H, J = 10.8 Hz), 5.92 (d, 1H, J = 17.4 Hz), 6.76 (dd, 1H, J = 10.8 Hz, J = 17.4 Hz), 7.55 (d, 2H, J = 8.4 Hz), 7.84 (d, 2H, J = 8.4 Hz), 9.99 (s, 1H).

N-Boc-4-aminostyrene$^{[2]}$:

A solution of 4-aminostyrene (4.49 g, 37.6 mmol) and di-tert-butyl dicarbonate (9.87 g, 45.2 mmol) in THF (100 mL) was heated at reflux under N$_2$ for 16 h. After evaporation to dryness crude material was transferred to a separating funnel in H$_2$O (50 mL) and the product was extracted with CH$_2$Cl$_2$ (3 × 50 mL). The organic extracts were combined and dried over Na$_2$SO$_4$, filtered, and evaporated to dryness to afford N-Boc-4-aminostyrene as a white solid (6.64 g, 80.3 %). $^1$H NMR (CDCl$_3$): δ 5.44 (d, 1H, J = 10.8 Hz), 5.92 (d, 1H, J = 17.4 Hz), 6.76 (dd, 1H, J = 10.8 Hz, J = 17.4 Hz), 7.55 (d, 2H, J = 8.4 Hz), 7.84 (d, 2H, J = 8.4 Hz), 9.99 (s, 1H).
Aldehyde-Functionalized Copolymer (P1):

δ-1-dodecyl-S’-(α,α-dimethyl-α’-acetic acid)trithiocarbonate (DDMAT) (1 eq, 57.5 mg, 0.158 mmol) and AIBN (0.2 eq, 5.2 mg, 31.6 µM) were added to a small schlenk tube. Styrene (65 eq, 1.07 g, 10.3 mmol) and 4-vinylbenzaldehyde (65 eq, 1.37 g, 10.3 mmol) was then added followed by dioxane (2.5 mL). The reaction mixture was degassed five times, and then the vessel was backfilled with N₂, purged with N₂, and allowed to warm to room temperature. The reaction mixture was then placed in an oil bath at 70 °C, and the polymerization was quenched after 24 h and solvent was removed on the rotary evaporator. The resulting yellow oil was dissolved in a minimal amount of THF and added dropwise to a large excess of ice-cold hexane. The polymer precipitate was then isolated by filtration and dried under high vacuum. Polymer P₁ was obtained as a pale yellow solid (1.77 g, 91%). ¹H NMR (CDCl₃): δ 0.84 (br, SC₁H₂CH₂, of the chain terminus), 1.42 (br, CHCH₂, polymer backbone), 1.61 (br, CHCH₂, polymer backbone), 3.29 (br, SCH₂C₁H₃, of the chain terminus), 6.53 (br, Ar, polymer backbone), 7.05 (br, Ar, polymer backbone), 7.02 (br, Ar, polymer backbone). The composition of P₁ can be determined simply by comparing the integration of the aldehyde protons with the total integration of the aromatic protons. The monomer composition was determined to be 1:1 styrene:vinylbenzaldehyde.

N-Boc-Protected Amine-Functionalized Copolymer (P2a):

δ-1-dodecyl-S’-(α,α-dimethyl-α’-acetic acid)trithiocarbonate (DDMAT) (1 eq, 52.1 mg, 0.143 mmol) and AIBN (0.2 eq, 4.7 mg, 28.6 µM) were added to a small schlenk tube. Styrene (75 eq, 1.12 g, 10.7 mmol) and N-boc-4-aminostyrene (75 eq, 2.35 g, 10.7 mmol) were then added followed by dioxane (3 mL). The reaction mixture was degassed five times and then the vessel was backfilled with N₂, purged with N₂, and allowed to warm to room temperature. The reaction mixture was then placed in an oil bath at 70 °C, and the polymerization was quenched after 22 h and solvent was removed on the rotary evaporator. The resulting yellow oil was dissolved in a minimal amount of THF and added dropwise to a large excess of ice-cold hexane. The polymer precipitate was then isolated by filtration and dried under high vacuum. Polymer P₂a was obtained as a pale yellow solid (1.18 g, 62%). ¹H NMR (CDCl₃): δ 0.89 (br, SC₁H₂CH₂, of the chain terminus), 1.38 (br, CHCH₂, polymer backbone), 1.55 (br, C(CH₃)), 1.76 (br, CHCH₂, polymer backbone), 3.29 (br, SCH₂C₁H₃, of the chain terminus), 6.53 (br, Ar, polymer backbone), 7.05 (br, Ar, polymer backbone). The composition of P₁ can be determined simply by comparing the integration of the Boc protons at δ = 1.55 ppm with the total integration of the aromatic protons. The monomer composition was determined to be 1:1 styrene:N-Boc-4-aminostyrene.

Amine-Functionalized Polymer (P2b):

TFA (1 mL) was added to a stirred solution of P₂a (0.1 g, 7.53 µM) in CH₂Cl₂ (1 mL) at room temperature. After 1 h the reaction mixture was evaporated to dryness to afford a crude yellow oil which was dissolved in minimal amount of THF and added dropwise to a large excess of ice-cold hexane. The polymer precipitate was then isolated by filtration and dried under high vacuum. Polymer P₂b was obtained as a pale yellow solid (0.09 g, 87%). ¹H NMR (THF-d₈): δ 0.85 (br, SC₁H₂CH₂, of the chain terminus), 1.45 (br, CHCH₂, polymer backbone), 1.79 (br, CHCH₂, polymer backbone), 3.29 (br, SCH₂C₁H₃, of the chain terminus), 6.56 (br, Ar, polymer backbone), 7.02 (br, Ar, polymer backbone), 7.44 (br, Ar, polymer backbone).

Aldehyde-Functionalized Diblock Copolymer (P3):

P₁ (1 eq, 1.02 g, 85 µM) and AIBN (0.2 eq, 2.8 mg, 17 µM) were added to a small schlenk tube. Styrene (300 eq, 2.66 g, 25.5 mmol) was then added followed by dioxane (3 mL) and the reaction mixture was degassed five times. The vessel was backfilled with N₂, purged with N₂, and allowed to warm to room temperature. The reaction mixture was then placed in an oil bath at 70 °C, and the polymerization was quenched after 24 h and solvent was removed on the rotary evaporator. The resulting yellow oil was dissolved in a minimal amount of THF and added dropwise to a large excess of ice-cold methanol. The polymer precipitate was then isolated by filtration and dried under high vacuum. Polymer P₃ was obtained as a pale yellow solid (3.03 g, 96%). ¹H NMR (CDCl₃): δ 0.89 (br, SC₁H₂CH₂, of the chain terminus), 1.43 (br, CHCH₂, polymer backbone), 1.86 (br, CHCH₂, polymer backbone), 6.57 (br, Ar, polymer backbone), 7.05 (br, Ar, polymer backbone), 7.52 (br, Ar, polymer backbone). 9.89 (br, CHO, polymer backbone).

Amine-Functionalized Diblock Copolymer (P4):

P₂a (1 eq, 1.05 g, 79 µM) and AIBN (0.2 eq, 2.6 mg, 15.8 µM) were added to a small schlenk tube. Styrene (400 eq, 3.29 g, 31.6 mmol) was then added followed by dioxane (4 mL) and the reaction mixture was degassed five times. The vessel was backfilled with N₂, purged with N₂, and allowed to warm to room temperature. The reaction mixture was then placed in an oil bath at 70 °C, and the polymerization was quenched after 25.5 h and solvent was removed on the rotary evaporator. The resulting yellow oil was dissolved in a minimal amount of THF and added dropwise to a large
excess of ice-cold methanol. The polymer precipitate was then isolated by filtration and dried under high vacuum. The pale yellow solid obtained was dissolved in CH\(_2\)Cl\(_2\) (3 mL) and TFA (3 mL) was added, solution was left to stir at room temperature. The reaction mixture was evaporated to dryness after 1 h, and the resulting crude yellow oil was dissolved in minimal amount of THF and added dropwise to a large excess of ice-cold hexane. The polymer precipitate was then isolated by filtration and dried under high vacuum. Polymer P4 was obtained as a pale yellow solid (1.11 g, 47%). ¹H NMR (CDCl\(_3\)): δ 0.89 (br, SC\(_{11}\)H\(_{22}\)CH\(_3\), of the chain terminus), 1.44 (br, CHCH\(_2\), polymer backbone), 1.87 (br, CHCH\(_2\), polymer backbone), 3.29 (br, SCH\(_2\)C\(_{11}\)H\(_{23}\), of the chain terminus), 6.59 (br, Ar, polymer backbone), 7.05 (br, Ar, polymer backbone).

Procedure for Macroscopic Gelation between P1 and P2b:

Solutions of P1 (0.5 and 5 wt %) in THF with TFA (10 eq) were prepared and allowed to stir at room temperature for 10 min to allow complete dissolution of the polymer sample. Solutions of P2b (0.5 and 5 wt %) were prepared in THF with TFA (10 eq) under identical conditions. Equal volumes of these corresponding solutions were mixed and gelation was observed in both cases after 15 min and 2h respectively.

General Procedure for the Preparation of CCS Polymers (1 – 6):

Solutions of the aldehyde functional diblock copolymer component P3 (0.5 – 5 wt %) were prepared in THF with TFA (10 eq). Solutions of the amine functional diblock copolymer component P4 (0.5 – 5 wt %) were also prepared under identical conditions. Equal volumes of corresponding solutions of the same concentration were combined with rapid stirring and left to equilibrate at room temperature for 16 h before GPC–MALLS analysis. GPC Analysis of all crude reaction mixtures reveals no evidence for any unreacted reactive polymers, indicating that the cross-linking reaction proceeds with 100% conversion.

Procedure for the Disassembly of CCS Polymers:

A sample of CCS polymers (2 mL, containing 2 wt % of polymer building blocks) was isolated. To this solution a large excess of propylamine (10 eq per aldehyde functional group) was added. The reaction mixture was left to stir overnight at room temperature before GPC analysis.

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Figure A. 1) dRI GPC traces (THF 1.0 mL/ min) of P1 and resulting diblock copolymer P3 after chain extension, 2) dRI GPC traces (THF 1.0 mL/ min) of P2a and resulting diblock copolymer P4 after chain extension. These chromatograms show the successful and complete chain extension of the macroinitiators P1 and P2a.
Table 1. Reaction conditions and characterization of polymers P1 – P4. * As determined by 1H NMR spectroscopy. † As determined by gel permeation chromatography in THF (1.0 mL/min) calibrated against polystyrene standards. ‡ As determined by online dynamic LS measurements.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Transfer agent</th>
<th>Monomer(s)</th>
<th>Initiator</th>
<th>Temp (°C)</th>
<th>Solvent</th>
<th>Time (h)</th>
<th>M_n (g mol⁻¹)</th>
<th>M_w (g mol⁻¹)</th>
<th>PDI</th>
<th>R_h (nm)</th>
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<tbody>
<tr>
<td>P1</td>
<td>DDMAE (1 equiv)</td>
<td>4-Vinylbenzaldehyde (65 equiv) Styrene (65 equiv)</td>
<td>AIBN (0.2 equiv)</td>
<td>70</td>
<td>Dioxane</td>
<td>21</td>
<td>12200</td>
<td>9200</td>
<td>10750</td>
<td>1.17</td>
</tr>
<tr>
<td>P2a</td>
<td>DDMAE (1 equiv)</td>
<td>N-(2-aminoethyl)styrene (75 equiv) Styrene (75 equiv)</td>
<td>AIBN (0.2 equiv)</td>
<td>70</td>
<td>Dioxane</td>
<td>22</td>
<td>13300</td>
<td>7350</td>
<td>8300</td>
<td>1.13</td>
</tr>
<tr>
<td>P2b</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>13800</td>
<td>8000</td>
<td>9000</td>
<td>1.13</td>
<td>2.6</td>
</tr>
<tr>
<td>P3</td>
<td>P1 (1 equiv)</td>
<td>Styrene (300 equiv)</td>
<td>AIBN (0.2 equiv)</td>
<td>70</td>
<td>Dioxane</td>
<td>24</td>
<td>37200</td>
<td>32000</td>
<td>43300</td>
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<tr>
<td>P4</td>
<td>P2 (1 equiv)</td>
<td>Styrene (400 equiv)</td>
<td>AIBN (0.2 equiv)</td>
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<td>Dioxane</td>
<td>25.5</td>
<td>30100</td>
<td>20250</td>
<td>28350</td>
<td>1.40</td>
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</tbody>
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Figure B. 1) 1H NMR spectra of aldehyde functional diblock copolymer P3, 2) 1H NMR spectra of amine functional diblock copolymer P4.
Figure 1. MALLS GPC traces of experiments 1 - 6 in THF (1.0 mL/ min).

Figure 2. dRI GPC traces of experiments 1 – 6 in THF (1.0 mL/ min).

Figure 3. a) Gelation of P1 and P2b in THF (0.5 wt %), b) Gelation of P1 and P2b in THF (5 wt %).
Figure 4. MALDI-TOF mass spectra of 2-arm core cross-linked star polymer.

Figure 5. dRI GPC traces indicating the decomposition of the CCS polymers prepared in Table 1 experiment 3 (dashed line) into block copolymers (solid line) after the addition of propylamine.

References: